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Characteristics of broken tops associated with forked crowns of ponderosa pine in central Oregon

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Broken top of a ponderosa pine at a v-shaped fork with embedded bark on the Deschutes National Forest, Bend-Fort Rock District

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Executive Summary

Broken tops can pose significant hazards along roadways and in developed recreation sites. Stem breakage can also reduce timber values, contribute to surface fuels and provide structures for wildlife habitat. Recently broken tops of ponderosa pine were observed on the Deschutes National Forest near Horse Butte in the winter and spring of 2012-2013. Strong winds during this period likely influenced much of the observed top breakage. The vast majority of top breakage appeared to occur at forks in mature ponderosa pine. The main objective of this study was to examine this important cause of structural instability in ponderosa pine to refine and validate both regional and local hazard tree guidelines. We analyzed: 1) whether certain easily measured bole characteristics influence the likelihood of top breakage at forks; 2) the distance away from the tree that broken tops landed, to assess potential failure zones; and 3) wind conditions under which top breakage might be expected. Areas within 350 ft of roads were surveyed at two sites for ponderosa pine with recently broken tops at forks in 2013 and 2015. Trees with forks but no broken tops (33 at each site) were randomly located for measurements as well. All study trees were revisited in 2014 to determine whether additional tops had broken at forks. In spring of 2015, sites were re-surveyed for additional broken tops at forks. During the initial survey at site 1, 40 trees had recently broken tops at forks across 838 acres surveyed and at site 2, 46 trees had recently broken tops at forks within 783 acres surveyed. During the 2015 survey, additional top breakage at forks was observed. It was common at both sites for trees to have multiple tops break at a fork. Approximately half of the study trees with broken tops had all tops break recently at the stem union of a fork and approximately half of them had half their tops (one of two) break recently at a fork. Based on logistic regression, diameter at breast height, the type of fork (u-shaped and v-shaped with or without embedded bark), height at which the fork occurred, mean length of tops above the fork, and mean length:diameter of tops above a fork were significant predictors of stem breakage. The vast majority of tops broke at v-shaped forks with embedded bark based on both surveys. Forks higher in trees (especially ≥ 46 ft) and forks with greater mean top lengths (especially ≥ 42 ft) were also more likely to break. Wind gusts up to 60 mph were recorded at a nearby weather station prior to the initial survey. Over 40% of broken tops on the ground were pointing away from prevailing winds during gusts ≥ 25 mph at both sites. The vast majority of broken tops at forks in ponderosa pine landed farther than one top length away from trees but 91% and 84% landed within 1.5 times the top length away at sites 1 and 2 respectively. Some trees had additional tops break at a fork, after initial stem breakage at the same fork, within one to one and half years. These surveys provide information about the frequency of trees with stem breakage at forks, and which stem characteristics are more likely to result in tree failure at forks, during similar wind disturbances in comparable ponderosa pine stands.

Introduction

One common location where tree failure can occur is at the union of forked or co-dominant stems during wind events (Gibbs and Greig, 1990). Based on static pulling tests, Kane and Clouston (2008) found that tree failures occurred at forks in large maples at approximately half the stress required for mainstem failures to occur in large maples without forks. Forked stems with embedded (also known as “inrolled or included”) bark are often more prone to breaking as well (Smiley, 2003; Harris et al, 2004; Slater and Ennos, 2015b). However, much of the research investigating the occurrence of stem breakage at forks has primarily involved deciduous trees and not conifers (Gibbs and Greig, 1990; Smiley, 2003; Kane and Clouston, 2008; Turner et al, 2012; Slater and Ennos, 2013; Slater et al, 2014; Slater and Ennos, 2015a; Slater and Ennos, 2015b; Buckley et al, 2015).

From a timber management perspective, having the ability to identify characteristics of forks that are reliable predictors of top breakage would be useful to help predict associated losses in stands managed to maximize volume during crop tree selection or thinning. Stem breakage in mature trees also influences decay development in live trees and snag recruitment, which affect wildlife habitat availability (Bull, 1987; Bull et al, 1997). Broken tops on the ground and in streams provide important structures for wildlife habitat as well (Smith and Maguire, 2004; Johnston et al, 2011). Information about characteristics of trees with forked crowns that are more prone to breaking, and therefore more likely to contribute to these types of habitat, could help forest managers select trees to leave or remove based on management objectives.

Having additional local knowledge about stem breakage at forks would also improve our understanding of the failure potential specific to ponderosa pine and provide useful information to those conducting hazard tree evaluations or planning hazard tree management along roads and within developed recreation sites. Currently the USDA Forest Service Pacific Northwest Region’s *Field Guide for Danger Tree Identification and Response* (Toupin et al, 2008) and the *Field Guide for Hazard-Tree Identification and Mitigation on Developed Sites in Oregon and Washington Forests* (Filip et al, 2014) include information about the failure potential of trees with forks. This survey provides an opportunity to compare observations following wind disturbances to information in these field guides to help validate recommendations. Recently broken tops (not present in early November 2012) of mature ponderosa pine were

Figure 1a. Broken top of a ponderosa pine.

Figure 1b. Ponderosa pine from which the top in Figure 1a. broke at a fork.

observed on the Deschutes National Forest (Bend-Fort Rock District) surrounding Horse Butte along portions of the Horse Butte Rd and portions of the NF-18 Rd (China Hat Rd). Much of the top breakage appeared to be associated with strong winds in late-November. Initial observations indicated stem breakage was not found on every tree and whole trees were not commonly blown over. Instead, broken tops were observed scattered throughout this location. The vast majority of tops that broke appeared to be at the basal junction of co-dominant stems (hereafter referred to as a fork) in the crowns of mature ponderosa pine (Figure 1). The main objectives of this survey were to determine whether easily measured stem characteristics of forked crowns could be used to help predict the likelihood of top breakage, how far from each tree broken tops landed, and estimate the types of wind conditions associated with top breakage.

Methods

Two sites were surveyed for recently broken tops at forks near Horse Butte on the Bend-Fort Rock District of the Deschutes National Forest in central Oregon (Figure 2). During an initial survey, data was collected from March to July of 2013. Sites were separated by at least one mile. Locations within 350 ft of roads were visually surveyed for detached tops of ponderosa pines that recently broke (with green or tan needles attached) at forks. Data were collected on tops that were ≥ 4” in diameter at the stem union. At site 1, an area of approximately 834 acres was surveyed along 12 miles of roads and at site 2, approximately 783 acres was surveyed along 12 miles of roads (Figure 3). Stand conditions consisted of dry ponderosa pine plant association groups (Simpson, 2007) in relatively open and clumpy, single- and two-aged stands. Based on Lidar-derived stand density data (acquired in 2010), total trees per acre ranged from 2 - 155 trees ≥ 5” in diameter at breast height (DBH) for stands within the area surveyed. A total of 33 trees were randomly located at each site with forks that did not have broken tops for data collection as well.

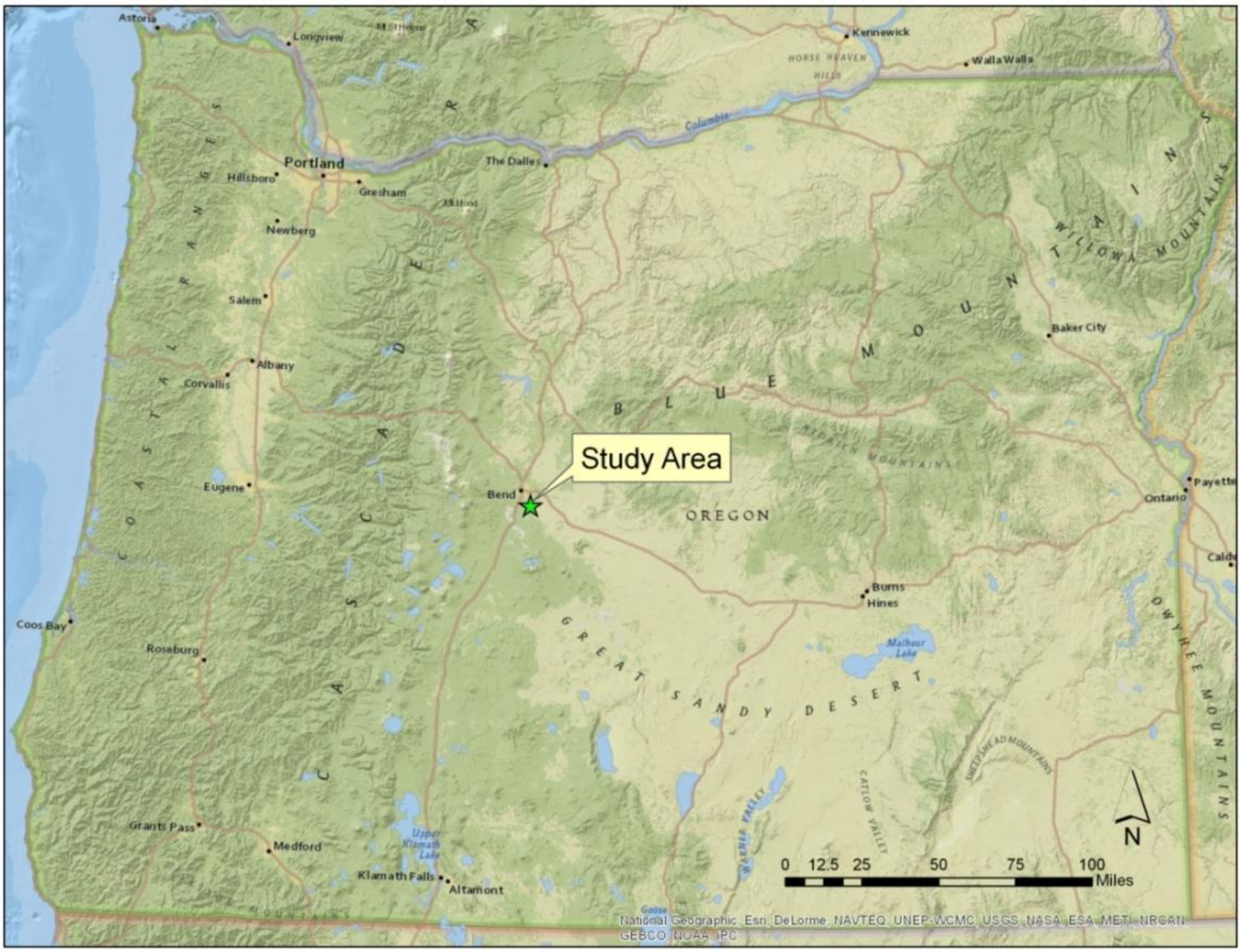
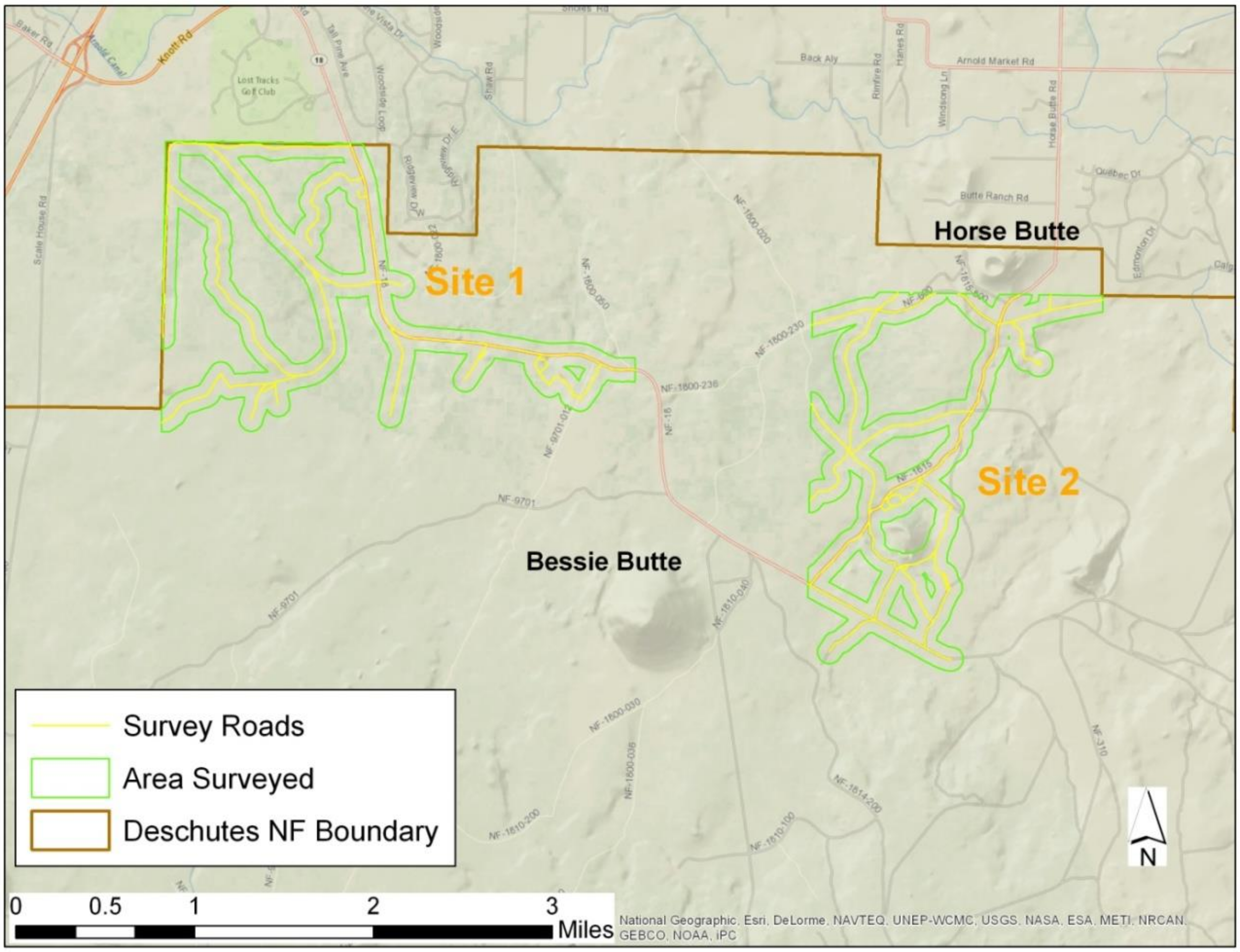


Figure 2. Study area where surveys were conducted for broken tops at forks in ponderosa pine on the Bend-Fort Rock District of the Deschutes National Forest in central Oregon.

Figure 3. Sites surveyed for broken tops at forks in ponderosa pine on the Deschutes National Forest southeast of Bend, Oregon.



Data collected for broken tops at forks of ponderosa pine in 2013 included: a) stem diameter to the nearest inch at the base of broken tops and immediately above the stem union (and above embedded bark and any swelling); b) the length of each broken top was measured to the nearest foot; c) whether the fork was u-shaped or v-shaped (Figure 4); d) the presence of embedded bark for tops which broke at forks (Figure 5) and for tops of trees with forks but without stem breakage (Figure 4b); e) the presence of decay at the base of each broken top.

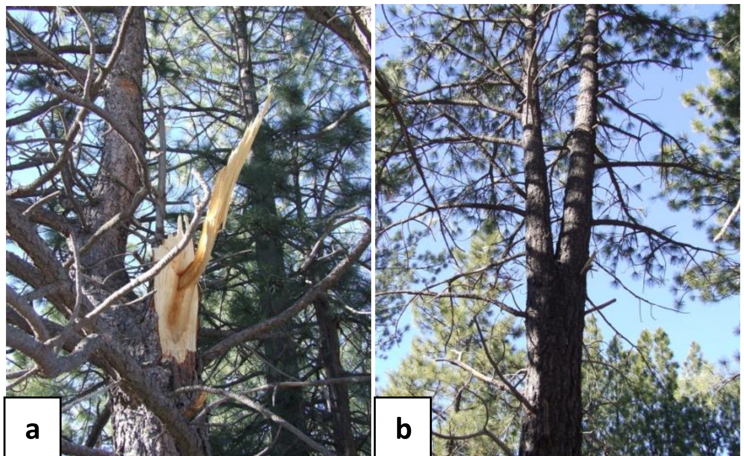


Figure 4.a) Ponderosa pine with a recently broken top at a u-shaped fork & b) ponderosa pine with a v-shaped fork with embedded bark.

Figure 5. A recently broken top at a v-shaped fork with embedded bark.

The following data was collected for each study tree in 2013 (with or without broken tops at forks): a) DBH to the nearest inch; b) total height; c) height at which forks occurred to the nearest foot; d) uncompacted live crown ratios (%) to the nearest 5% were determined visually based on total heights; e) diameter of tops immediately above the stem union (and above embedded bark and any swelling) was measured to the nearest inch.

Trees that had broken tops at forks were then compared to trees with forked crowns but without broken tops to assess whether site, tree characteristics or fork characteristics were significant predictors of stem breakage at forks. Means were calculated for trees that had broken tops at forks and for trees with forks but without stem breakage. Statistical analyses were completed using JMP software, version 7 (2007, SAS Institute Inc., Cary, NC, USA). Nominal logistic regression (fit model command) was used to model the probability of stem breakage at a fork for trees observed with recently broken tops at forks and 33 randomly located trees at each site with forks but without broken tops. Logistic models were evaluated by assessing the Whole Model Test based on the Chi-square statistic ($\alpha = 0.05$), Lack of Fit Test based on the Chi-square statistic ($\alpha = 0.05$), comparisons of the Area Under the Receiver Operating Characteristic Curve (AUC), the logit r^2 value, and statistics for significance of individual parameters using Chi-square tests ($\alpha = 0.05$). Chi-square statistics ($\alpha = 0.05$) were used to test for effects of: 1) site; 2) DBH; 3) fork type (u-shaped or v-shaped with and without embedded bark); 4) height at which forks occurred; 5) mean length of tops above the fork; 6) mean diameter of tops immediately above the stem union; 7) mean top length:diameter ratio; 8) number of tops above the fork; and 9) interactions between them.

For recently broken tops detected in 2013 lying on the ground, distance from the bole was measured to the farthest point of each top to the nearest foot. Distances were grouped and represented as a percentage of the total number of broken tops on the ground at that distance in order to assess the failure zones.

To examine whether there were patterns between winds and stem breakage, directional data were gathered for winds and broken tops. Orientation (in true degrees, from base-to-leader) was measured for all tops lying on the ground in 2013. Orientations were then grouped into classes based on 45° intervals (of 1 - 360°). Wind speed and direction data were acquired from the nearest weather station at Lava Butte (RAWS USA Climate Archive, 2013) approximately 4.5 - 6.5 miles southwest of locations within each site. To estimate whether tree density had an effect on stem breakage at forks, the number of trees ≥ 5” DBH surrounding all study trees was estimated using Lidar-derived data (acquired in 2010).

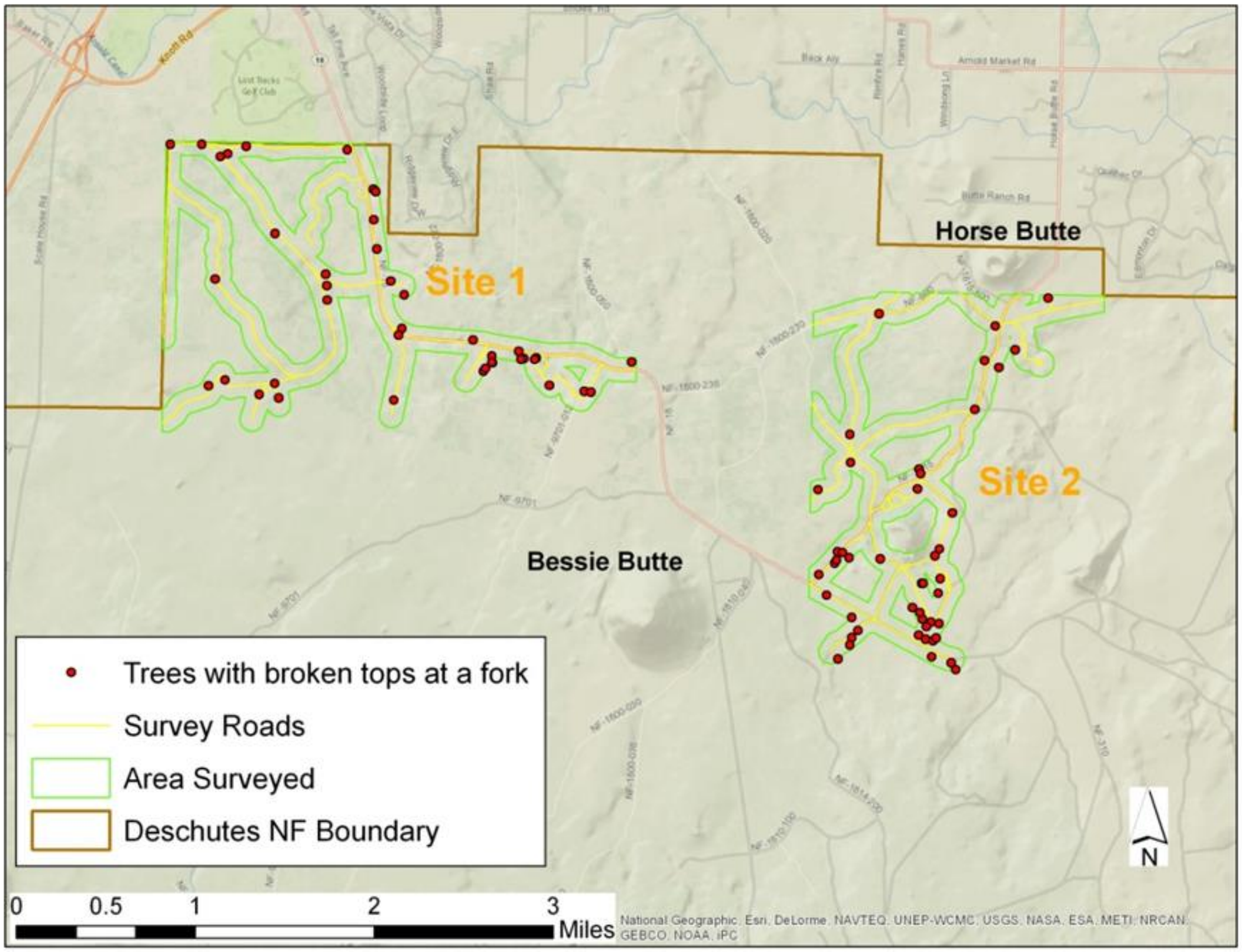
In July of 2014, all trees surveyed that were alive during 2013 were revisited to see if additional mortality had occurred after live crown ratios were reduced as a result of stem breakage at forks. Trees from the initial survey with tops still attached at forks where a top(s) had previously broken in the last year were revisited. These trees were examined to determine whether additional tops had broken within approximately a year and a half.

In March and early-April of 2015, both sites were re-surveyed for additional trees with broken tops at forks that had failed after the initial survey in 2013 to include multiple wind events. Data collected for recently broken tops in 2015 included: a) the number of broken tops at each fork; b) whether the fork was u-shaped or v-shaped; d) the presence of embedded bark at the fork; and e) the presence of decay at the base of each broken top.

Results

Stand characteristics, study tree characteristics and frequency of recently broken tops at forks were similar at both sites. During the initial 2013 survey, there were 40 ponderosa pines that had recently broken tops at forks detected within approximately 834 acres surveyed at site 1, and 46 ponderosa pines with recently broken tops at forks were detected within approximately 783 acres at site 2 (Figure 6). Areas where broken tops were observed often had similar tree densities to areas where stem breakage did not occur at forks. Where top breakage occurred at forks, total trees ≥ 5” DBH ranged from 14-90 trees per acre for stands in the area surveyed at site 1 and ranged from 6 to 88 trees per acre at site 2. Basal area was variable due to openings, clumps of trees and overall different tree densities present. Tree heights also varied but nearly all trees were less than 100 ft tall (many were roughly 50-90 ft tall). For trees with forks but without broken tops that were randomly located for stem measurements, total trees per acre > 5” DBH, ranged from 15-100 for stands in the area surveyed at site 1 and ranged from 6-155 at site 2.

Figure 6. Distribution of ponderosa pines with a recently broken top(s) at a fork in 2013.



Trees with broken tops at forks had a mean DBH of 21 ± 0.7 - 0.8" S.E. at both sites and trees without broken tops at forks had a mean DBH of 18 ± 1.1" S.E. at site 1 and 19 ± 0.9" S.E. at site 2. Trees with broken tops at forks had an estimated mean total height before stem breakage of 79 ± 2 ft S.E. at site 1 and 74 ± 2 ft S.E. at site 2. Trees with forks but no broken tops at site 1 had a mean total height of 68 ± 3 ft S.E. and 59 ± 2 ft S.E. at site 2. The mean diameter of broken tops at the breaking point was 11 ± 0.6" S.E. (range 4-33") at site 1 and 10 ± 0.4" S.E. (range 5-22") at site 2. The vast majority of broken tops at bifurcations had very similar diameters near their stem union (high diameter ratios). The mean length of broken tops was 45 ± 2.2 ft S.E. (range 20-81 ft) at site 1 and 40 ± 1.9 ft S.E. (range 14-86 ft) at site 2. At both sites, some trees appeared to have forks form as a result of previous rodent girdling (e.g., porcupine). No advanced decay was found at the base of any broken tops at the stem union and no evidence of advanced decay was detected at forks in trees without broken tops.

However, evidence of past partial failure (previous splitting) was found occasionally in broken tops based on dried, discolored resin over sapwood at the stem union.

Some trees at both sites had multiple tops break at a fork and a total of 64 recently broken tops at forks were observed at site 1 and 71 at site 2. Bifurcations were common where broken tops occurred. It was common for trees with two to four tops at a fork to have all tops break recently or half of their tops break recently at a fork (Table 1). Low levels of tree mortality were observed due to recent stem breakage at forks. There were three of 40 trees with broken tops at forks that had no live crown following stem breakage at site 1 and two of 46 trees at site 2 in 2013 (Figure 7).

Table 1. For trees with top breakage at a fork in 2013, percentage with single and multiple tops recently breaking.

No. tops that broke out of the total at each fork	Site 1	Site 2
1 of 3	0%	2%
1 of 2	48%	44%
2 of 4	2%	2%
2 of 2	50%	52%

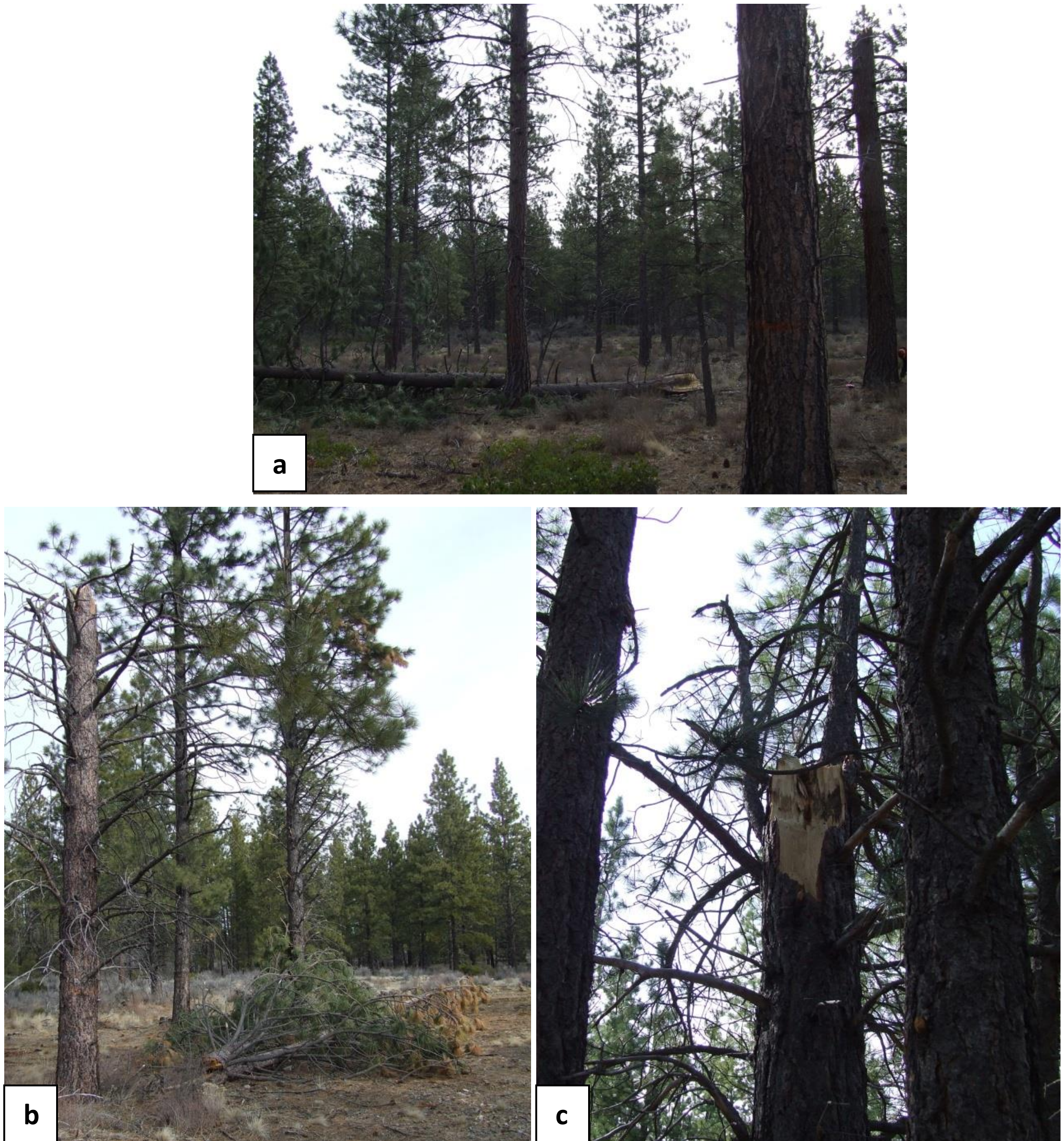


Figure 7.a-c) Ponderosa pines killed due to recent stem breakage at a fork.

The logistic model described expected probability of stem breakage ($p < 0.0001$ based on Whole Model Test and $p > 0.11$ based on Lack of Fit Test) at forks for 152 trees based on 2013 survey data. The AUC = 0.80 and the logit $r^2 = 0.21$. Site was excluded since it was not a significant predictor in the model ($p > 0.11$) when other predictors were included. Interaction terms also were excluded because they did not improve model fit. Number of tops and mean diameter of tops at the fork did not have significant effects (values of $p > 0.21$) on the likelihood of stem breakage. DBH, fork type, height at which the fork occurred, mean length of tops and mean length:diameter ratio of tops had significant effects on stem breakage (values of $p <$ 0.0001 – 0.026). Model parameter estimates are shown below (Table 2).

Table 2. Logistic model parameters for likelihood of stem breakage at a fork.

Parameter[1]	Coefficient Estimate	Standard Error	Chi-square value	P value
Intercept	-1.44	2.80	0.07	0.80
DBH	-0.20	0.08	7.15	0.008
U-shaped fork	-0.79	0.59	1.83	0.18
V-shaped fork with embedded bark	0.49	0.54	0.81	0.37
Height at which fork occurred	0.10	0.03	13.82	0.0002
Mean length of tops above fork	0.16	0.06	6.02	0.01
Mean diameter of tops above fork	-0.07	0.25	0.07	0.80
Mean length:diam. of tops above fork	-0.10	0.05	4.56	0.03
Number of tops above fork	0.84	0.72	1.38	0.24

[1]Model parameters in bold were significant ($p < 0.05$) based on the Wald z-statistic. Coefficient estimates and statistics for fork types are based on likelihood of stem breakage compared to v-shaped forks without embedded bark.

With each one foot increase in height at which a fork occurred, a fork was 1.10 times more likely to break. For each one inch increase in DBH, likelihood of stem breakage at a fork decreased (0.82 times as likely). With each one foot increase in mean length of tops, forks were 1.17 times more likely to break. Forks with higher mean length:diameter ratios of tops above the stem union were slightly less likely (0.91 times) to break per unit increase in ratio. Using a probability threshold of >0.50 for estimating likelihood of top breakage at a fork with the logistic model, 79.4% of the cases were correctly classified as having a broken top at a fork or not.

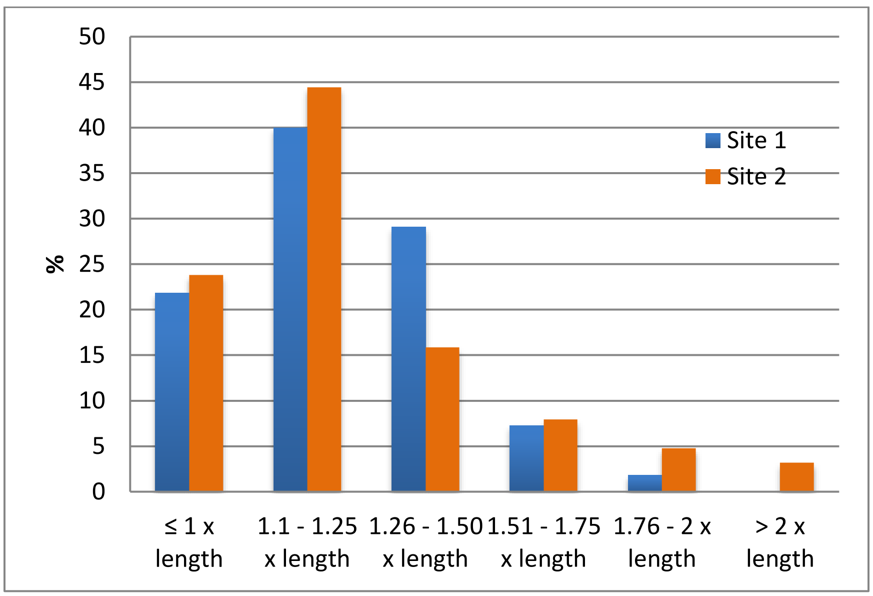
Nearly all broken tops that occurred at a v-shaped fork had some amount of embedded bark (only one at each site did not have embedded bark). V-shaped forks with embedded bark were 3.6 times more likely to break than u-shaped forks. Of all trees with broken tops at a fork, the vast majority of stem breakage occurred at a v-shaped fork rather than a u-shaped fork (Table 3).

Table 3. Percentage of trees with recent stem breakage at each fork type.

Fork type	Site 1	Site 2
Trees with u-shaped forks that broke	15%	11%
Trees with v-shaped forks with embedded bark that broke	83%	87%
Trees with v-shaped forks without embedded bark that broke	2%	2%

It also was common for portions of broken tops to land farther than 1 times (x) the top length away from trees that failed (Figure 8).

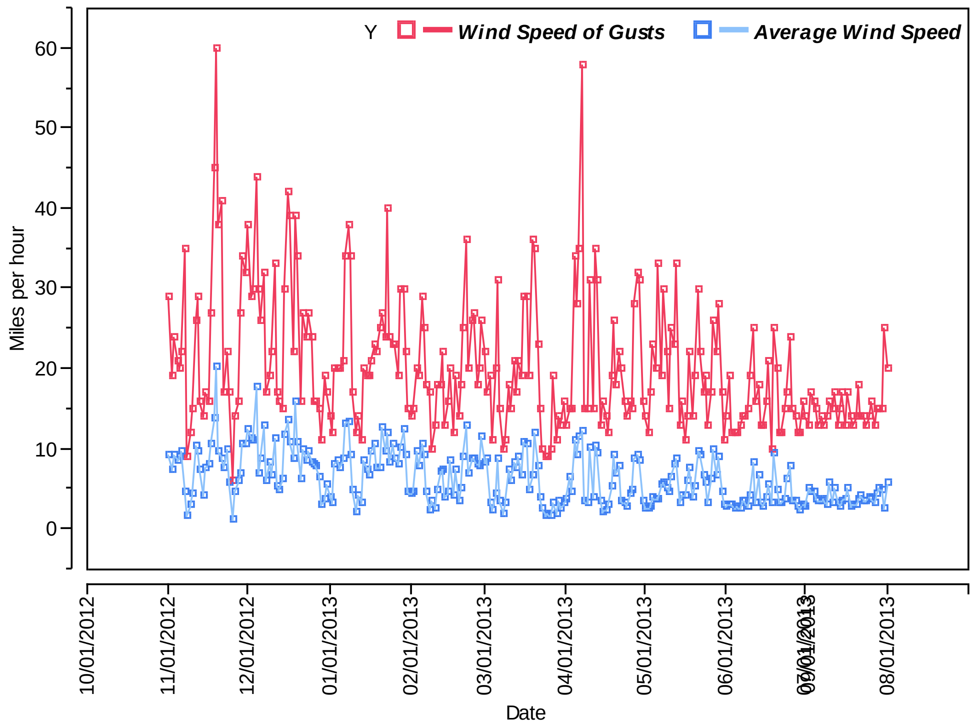
Figure 8. Percentage of broken tops by failure zone.



Some recently broken tops even landed farther than 2 x the top length away. However, 91% and 84% of tops landed within 1.5 x the top length away at sites 1 and 2 respectively.

Strong winds were recorded near the study area at times (Figure 9) during the period when broken tops were first observed until data were collected in 2013 with the strongest winds being recorded on November 19, 2012 with 60 mph gusts and an average wind speed of 20 mph. Gusts > 40 mph occurred at other times in November and December of 2012 and in April of 2013. Wind disturbances such as these likely contributed to observed stem breakage.

Figure 9. Average daily wind speed and maximum speed of gusts recorded at Lava Butte, Oregon from November 1, 2012 - August 1, 2013.



Broken tops were oriented (from base to leader) in various directions on the ground (Figure 10) and some appeared to have toppled on impact end-over-end. However, out of all eight orientation classes, the class containing the most broken tops at both sites was north-northeast (1 - 45°) and more than 60% of all tops on the ground were oriented 1-90° at both sites. Broken tops oriented this way were pointing away from prevailing wind directions during stronger gusts (≥ 39 mph), which were from the south-southwest or southwest (Figure 11). Nearly all prevailing wind directions when gusts > 31 mph (when whole trees are in motion according to the Beaufort Wind Scale, Appendix A) were recorded came from the south-southwest or southwest (Figure 11).

Figure 10. Percentage of recently broken tops pointed in various directions (45° intervals).

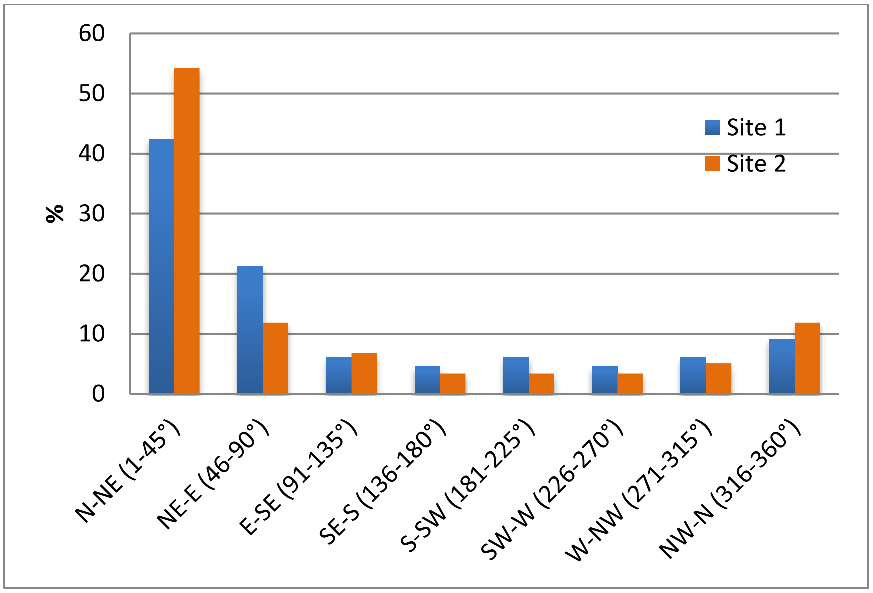
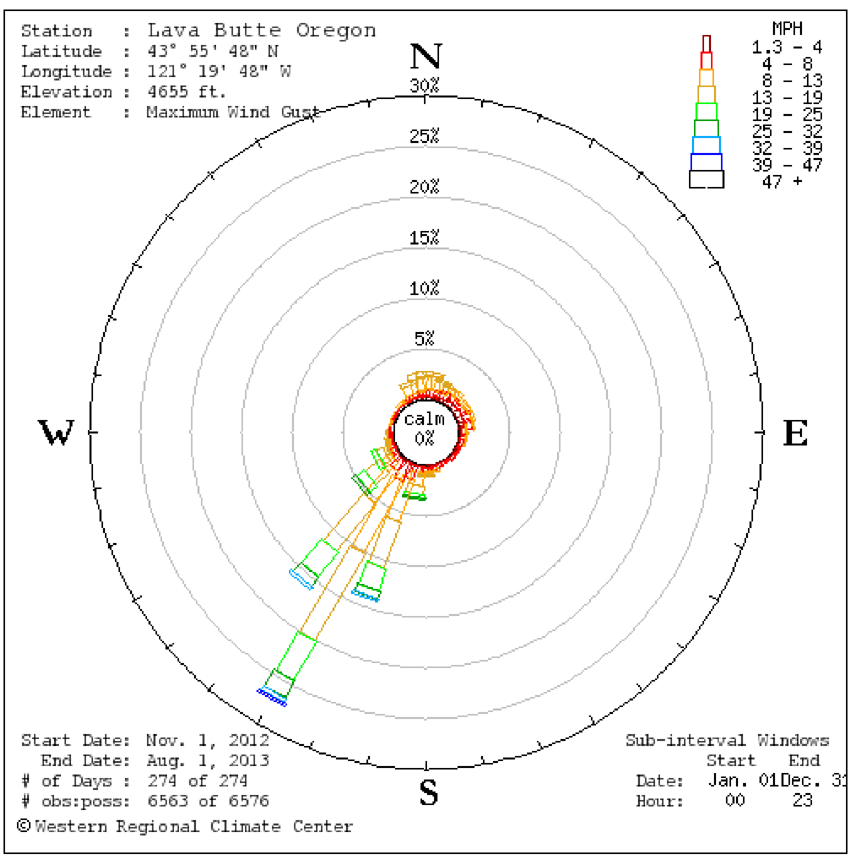


Figure 11. Percentage of wind gusts (Beaufort scale, see Appendix A) coming from different directions from November 1, 2012 - August 1, 2013 recorded at Lava Butte, Oregon.



In 2014, additional mortality of study trees with broken tops at forks occurred in those with low live crown ratios following stem breakage. Three additional trees died at site 1 and four additional trees died at site 2 within approximately one to one and a half years after the initial survey. Of these killed trees, all except one had live crown ratios of ≤10% the year before. Bark beetles (including mountain pine beetle, *Ips* sp., western pine beetle and red turpentine beetle) were observed attacking trees that were recently killed.

For study trees revisited in 2014 with a top(s) still attached at a fork during the initial 2013 survey, additional stem breakage was observed at forks of trees that failed previously. Three trees had an additional top(s) break at a fork of 21 trees at site 1 (of those with a top(s) attached where a top broke initially at a fork) and three trees at site 2 out of 25. No control trees had a broken top when revisited in 2014.

During the 2015 survey for additional trees with broken tops at forks approximately two years after the initial survey in 2013, 10 and 11 additional trees were observed with a recently broken top(s) at a fork at sites 1 and 2 respectively. After both surveys, a total of 50 trees at site 1 and 57 trees at site 2 were detected with a recently broken top(s) at a fork. More trees appeared to have half their tops break recently at forks than have all their tops recently break during this survey compared to the initial survey. At site 1, six of 10 had half their tops (one of two) break recently at a fork and four of 10 had all their tops (two of two) break recently. At site 2, seven of 11 trees had half their tops (one of two) break recently at a fork and four of 11 had all their tops (two of two) recently break. Compared to the initial survey, the majority of broken tops again occurred at v-shaped forks with embedded bark but a higher percentage of tops broke at u-shaped forks at site 2 compared to results from the initial survey. At site 1, all 10 trees had recently broken tops at a v-shaped fork with embedded bark. At site 2, six of 11 had recently broken tops at a v-shaped fork with embedded bark and five of 11 had broken tops at a u-shaped fork without embedded bark. Between the 2013 and 2015 surveys, similar wind patterns were observed at the Lava Butte weather station with gusts up to 57 mph (in February of 2015) and the strongest winds were most-often recorded during winter and spring months and almost always from the south-southwest or southwest.

Discussion & Conclusions

Wind conditions likely affected results of these surveys. If different wind speeds or directions had occurred, other patterns may have emerged. Local topography and stand conditions affecting wind-loading also could have influenced stem breakage at forks. Fons and Pong (1957) found that during static pull tests of ponderosa pine without forks that trees growing on poor, less productive sites required more energy to break than trees growing on better, more productive sites. Even though more top breakage at forks could be expected during the strongest wind events that most-often occur during the winter and spring in central Oregon, winds >31 mph were recorded during other times of year, including summer and fall based on weather local data analyzed from 2012-2015. If climate change results in a higher frequency of storms with strong winds, broken tops at forks (and whole tree failure) may also occur more frequently. Stem breakage is influenced by the presence/absence of interlocking xylem in wood at the apex of forks compared to forks with included bark (Slater and Ennos, 2013; Slater et al, 2014) or by the moisture content and temperature within the wood during wind events as well. The amount of included bark at stem unions and shape of the bifurcation (wide-mouthed, cup-shaped, etc.) may also influence the strength of a stem union (Slater and Ennos, 2015b). The angle of inclination may also affect the strength of a bifurcation (Buckley et al, 2015). Differences in wood strength could vary throughout the range of ponderosa pine and could have an effect on tree failure at forks. The total number of trees with forks was not determined within the surveyed area. The overall abundance of trees with forked crowns could have influenced how many trees with broken tops at forks were observed and where they were concentrated. Some trees with forks in stands surveyed appeared to have forks form due to past porcupine damage but the extent of forks forming due to porcupine or rodent damage was not part of this survey. These factors may explain why fewer trees with recently broken tops at forks were observed at sites during the 2015 survey compared to the initial 2013 survey.

During similar wind events with gusts up to 55-60 mph in comparable stands of ponderosa pine, forest managers and those involved with hazard tree management could expect more stem breakage in trees with forks that are v-shaped with embedded bark, higher up the mainstem (especially ≥ 46 ft up based on a probability of breaking ≥ 0.70), and that also have longer tops above the fork (especially with a mean top length of ≥ 42 ft long based on a probability of breaking ≥ 0.70). We were surprised to observe forks with tops having a higher length:diameter ratio being slightly less prone to breaking but that may be due to these tops having thinner crowns and less wind loading. All tops breaking at a fork, or one of two tops breaking at a fork, could commonly occur within relatively short time frames based on survey results. Based on the 2015 survey, tree failure at forks in ponderosa pine could occur repeatedly at specific locations if trees with forks are still present over time, especially in areas exposed to wind. For example at site 2, nearly all additional trees with broken tops at forks approximately two years after the initial survey were in southern portions of the area surveyed, which is the same area where the majority of broken tops at forks were observed in 2013. In addition to certain sites being more prone to recurring stem breakage at forks, some trees with a previously broken top at a fork but with another top still attached, could have another top(s) break at the same fork within a year and a half or less in some cases.

From a hazard tree perspective, the vast majority of broken tops were > 20 feet long and weighed enough to have caused substantial damage if a target (such as a parked vehicle, passing vehicle on the road, people in a campground or picnic area, etc.) was present within striking distance. Broken tops lying on roads also present hazards to people traveling in vehicles and could result in injury and damage to vehicles. The majority of broken tops landed farther than 1 x the top length away from trees as well and targets outside this radius could potentially be impacted by tops breaking at forks in ponderosa pine.

Tree failures commonly occur in ponderosa pine at forks elsewhere east of the Cascades based on our observations and those made by others (e.g., Schmitt, 2013 personal communication). There is both agreement and disagreement between what was observed and information regarding forks in the USDA Forest Service Pacific Northwest Region's hazard tree field guides (Toupin et al, 2008; Filip et al, 2014). We found that a portion of broken tops frequently landed farther than 1 x the top length away from trees and a small number (3%) of tops even landed farther than 2 x the top length away at site 2. In the USDA Forest Service Pacific Northwest Region's *Field Guide for Danger Tree Identification and Response* (Toupin et al, 2008), 1.5 x the top length is recommended for the potential failure zone when examining possible danger trees along roads or in workplace settings and 1 x the top length is recommended for the potential failure zone of hazard trees in the *Field Guide for Hazard-Tree Identification and Mitigation on Developed Sites in Oregon and Washington Forests* (Filip et al, 2014). At the two sites surveyed in 2013, 9% and 16% of broken tops landed farther than 1.5 x the top length away. Due to bending in ponderosa pine, broken tops could be propelled and potentially damage targets at times farther than 1 to 1.5 x the length of the top away.

These field guides (Toupin et al, 2008; Filip et al, 2014) and other literature (Smiley, 2003; Harris et al, 2004) emphasize that trees with forks containing embedded bark are more likely to fail, which is consistent with what we observed. The field guides explain that u-shaped forks have low failure potential and rarely fail. Although less common, we observed multiple tree failures at u-shaped forks as well (especially at site 2 during the 2015 survey), which may occur more frequently in ponderosa pine during high wind events. To reduce the risk of tree failure at forks in ponderosa pine, developed sites with more forks present in ponderosa pine growing in more open areas exposed to winds, could be prioritized for hazard tree surveys and management in central Oregon.

Trees with broken tops also play important ecological roles. Various wildlife species depend on down woody debris for habitat (e.g., Smith and Maguire, 2004) and broken tops at forks contributed to down woody debris inputs in stands surveyed. Broken tops on the ground also affect surface fuel loads, which influence wildland fire behavior, severity and intensity. Tree mortality due to stem breakage at forks was observed as well. Live and dead trees with broken tops could contribute to snag development and structures important to wildlife (Bull et al, 1997; Bull, 1987). These surveys provide additional information about which ponderosa pines are more likely to have broken tops at a fork, and which trees could contribute to snag recruitment during similar wind events. Certain bark beetles and other insects (such as the Ips pine engraver (*Ips pini*) and wood borers) also colonize broken tops and if numerous broken tops are present, bark beetles could potentially cause topkill or tree mortality in nearby standing trees (Furniss and Carolin, 1977). In areas where ponderosa pine stands are actively managed for timber, ecological values, or hazard tree mitigation, the risk of top breakage in trees with forks should be considered.

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Appendix A.

Beaufort Wind Scale (Estimated wind speeds)

Beaufort number	Wind speed			Mean wind speed (kt / km/h / mph)	Description	Land conditions
	kt	km/h	Mph			
0	0	0	0	0 / 0 / 0	Calm	Calm. Smoke rises vertically.
1	1-3	1-6	1-3	2 / 4 / 2	Light air	Wind motion visible in smoke.
2	4-6	7-11	4-7	5 / 9 / 6	Light breeze	Wind felt on exposed skin. Leaves rustle.
3	7-10	12-19	8-12	9 / 17 / 11	Gentle breeze	Leaves and smaller twigs in constant motion.
4	11-15	20-29	13-18	13 / 24 / 15	Moderate breeze	Dust and loose paper is raised. Small branches begin to move.
5	16-21	30-39	19-24	19 / 35 / 22	Fresh breeze	Smaller trees sway.
6	22-27	40-50	25-31	24 / 44 / 27	Strong breeze	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult.
7	28-33	51-62	32-38	30 / 56 / 35	Near gale	Whole trees in motion. Effort needed to walk against the wind.
8	34-40	63-75	39-46	37 / 68 / 42	Gale	Twigs broken from trees. Cars veer on road.
9	41-47	76-87	47-54	44 / 81 / 50	Severe gale	Light structure damage.
10	48-55	88-102	55-63	52 / 96 / 60	Storm	Trees uprooted. Considerable structural damage.
11	56-63	103-119	64-73	60 / 112 / 70	Violent storm	Widespread structural damage.
12	64-80	120	74-95	73 / 148 / 90	Hurricane	Considerable and widespread damage to structures.